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Helmi, Amina; Navarro, Julio F.; Meza, Andrés; Steinmetz, Matthias; Eke, Vincent R.

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## The Nature of the Ring-Like Structure in the Outer Galactic Disk

Amina Helmi

*Astronomical Institute Utrecht, P.O. Box 80000, 3508 TA Utrecht, and  
Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen,  
The Netherlands*

Julio F. Navarro and Andrés Meza

*Department of Physics and Astronomy, University of Victoria, Victoria,  
BC V8P 1A1, Canada*

Matthias Steinmetz

*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482  
Potsdam, Germany, and Steward Observatory, 933 North Cherry  
Avenue, Tucson, AZ 85721, USA*

Vincent R. Eke

*Physics Department, Durham University, South Road, Durham DH1  
3LE, UK*

**Abstract.** The tidal disruption of a satellite galaxy can leave behind substructures, such as tidal tails, streams, or shells. Satellites moving on orbits roughly coplanar with the Galactic disk, will deposit most of its debris in this component. We show here that this process leads naturally to the formation of ring-like stellar structures similar to that recently discovered in the outer disk of the Milky Way.

### 1. Introduction

Surveys like the Sloan Digital Sky Survey (SDSS) are starting to reveal tantalizing hints of substructure in our Galaxy, thereby reshaping our understanding of the structure and dynamics of the Galaxy (Newberg et al. 2002). The most recent example is the discovery of a coherent structure at large Galactocentric distance and low galactic latitude spanning about  $100^\circ$  on the sky (Yanny et al. 2003, hereafter Y03; Ibata et al. 2003, hereafter I03). The structure, of thickness  $\sim 2\text{--}4$  kpc (part of which may be due to photometric errors), is located at a roughly constant distance of 20 kpc to the Galactic Center across the  $100^\circ$  in longitude, and its internal velocity dispersion is  $\sim 20\text{--}30$  km s $^{-1}$ .

The nature of this “ring” is currently being vigorously explored. Y03 suggested that it could be the debris of a tidally disrupted satellite moving in a roughly circular orbit. This interpretation may seem unlikely given the observed orbital distribution of the satellites of our Galaxy as well as of those found in cosmological simulations of dark matter halos. Dynamical friction could be invoked as a way of circularizing an initially eccentric orbit, although the effectiveness

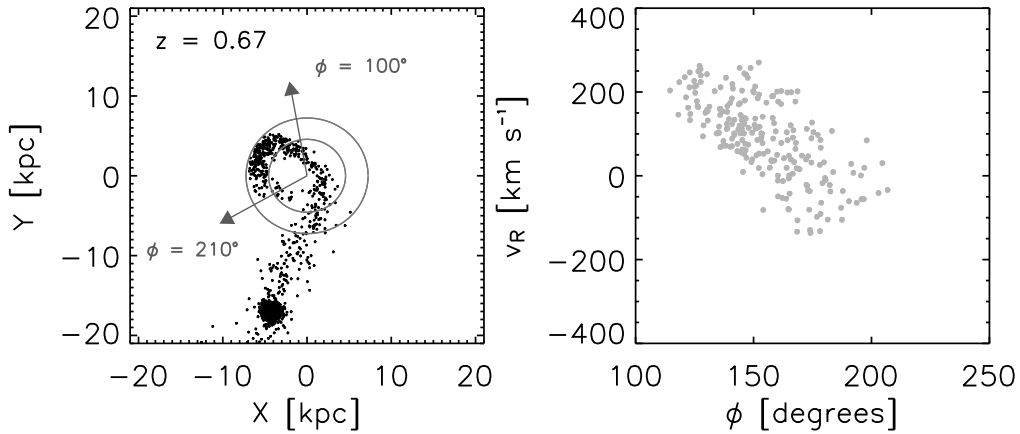


Figure 1. Snapshot of the disruption of a satellite in an orbit roughly coplanar to the disk, taken from the simulation of Abadi et al. (2003). The left panel shows a “face on” projection of the debris. The right-hand panel shows, in a cylindrical coordinate system, the (Galactocentric) radial velocity versus azimuthal angle  $\phi$  for particles in the arc delimited in radius by the two concentric circles of the left panel.

of this process is still under debate. It is not clear how likely it is for the debris of a disrupted galaxy to remain as a sharp feature at 20 kpc from the Galactic Center while being stretched over one hundred degrees on the sky.

I03 preferred the hypothesis that the ring results from perturbations in the disk, such as the remnants of ancient warps. But would a disk instability preferentially select metal-poor stars in such a distant ring around the Galaxy? It is not clear either whether a warp or flare could produce a structure as observed, particularly given that the H I warp of the Milky Way has a different orientation.

Since the La Palma meeting, several new studies have been made to address the nature of this ring; they are summarized in the Section 3. In what follows we discuss some insights that can be gained from cosmological simulations.

## 2. Insight from (Cosmological) Simulations

In any cosmological simulation of the formation of a disk galaxy, some fraction of the satellites will be in low inclination orbits, by which we mean  $\sim 30^\circ$ – $45^\circ$  with respect to the plane of the disk. Such low inclination satellites are drawn by dynamical friction to the centers of their hosts galaxies, and by interactions with a pre-existing disk, they deposit their debris at increasingly lower inclinations.

In Figure 1 we show the properties of debris from a satellite from the cosmological simulation of Abadi et al. (2003). The left panel shows that young debris is distributed along a ring-like structure, in many ways analogous to that reported by Y03 and I03. Most stars with  $4.6 \text{ kpc} < R < 7.2 \text{ kpc}$  and  $100^\circ < \phi < 210^\circ$  were stripped from the satellite during its first pericentric passage, and are now going through the apocenter of their orbits.

The panel on the right in Figure 1 shows the radial velocity (in cylindrical coordinates) as function of azimuthal angle as would be observed from the Galactic

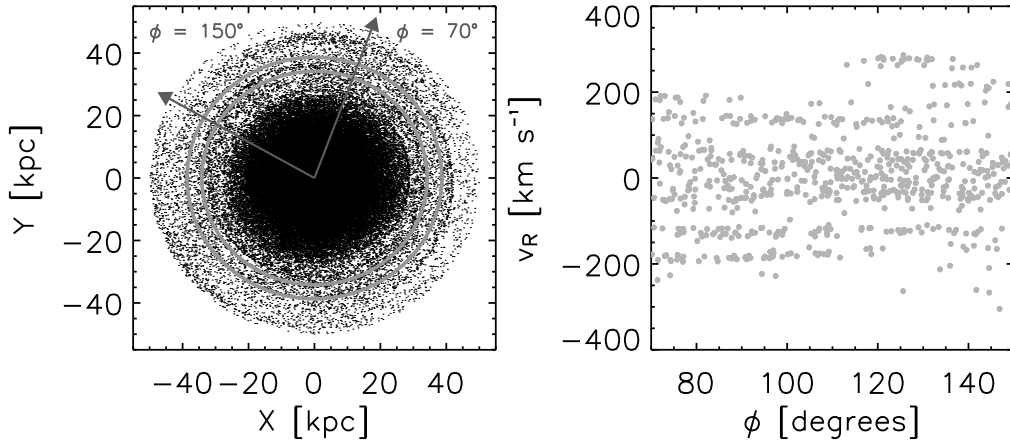


Figure 2. Same as Figure 1, but for a spherical satellite modeled after that extracted from the cosmological simulation, moving in a fixed potential. The debris is shown at  $z = 0$  and illustrates the persistence of density enhancements of constant radii (“shells”).

Center. The most salient property of arcs is the presence of a well-defined radial velocity gradient across the structure. The (Galactocentric) radial velocity varies by almost  $200 \text{ km s}^{-1}$  across  $50^\circ$  in azimuthal angle; however, at any given location, the velocity dispersion is fairly small. Arcs span a limited azimuthal range, which depends both on the location of the observer, as well as on the eccentricity of the satellite’s orbit at the time of stripping. Interestingly, the angular extent of the arc shown in Figure 1 ( $\Delta\phi \sim 100^\circ$ ) is comparable to that of the structure observed by Y03 and I03. We also note that particles on the arc are in quite eccentric orbits: their  $R_{\text{per}}/R_{\text{apo}} \sim 0.18$ .

Tidal features like the “arcs” shown in Figure 1 are transitory, lasting only a few crossing times. There exist, however, other long-lasting features in physical space like the shells often found around elliptical galaxies. To be able to resolve the substructures left over by the merged satellite by the present time, we have run a high resolution simulation of the disruption of a  $10^6$ -particle satellite (modeled after that shown in Figure 1) in a fixed galactic potential.

The left panel in Figure 2 shows a “face-on” view of the satellite debris 7 Gyr after infall: several sharply defined ring-like features are easily identified in this panel, especially in the outer regions. To illustrate the properties of these features, we choose the annulus defined by  $34.7 \text{ kpc} < R < 37.1 \text{ kpc}$  and  $70^\circ < \phi < 150^\circ$ . The panel on the right of Figure 2 shows that there are no gradients in the radial velocity across the “shell”. The radial velocity distribution at any given location on the shell has several components but is dominated by a central core, comprising  $\sim 70\%$  of the stars, with small velocity dispersion.

Shells are relaxed features that, contrary to “arcs”, are roughly symmetric above/below the plane of the disk. They are long-lived, but it is unlikely that they may carry a significant fraction of the original mass of the satellite: the shell shown in Figure 2 contains only  $0.7\%$  of the satellite’s mass, an order of magnitude smaller than the fraction of mass carried by the arc shown in Figure 1.

### 3. Discussion

Since these results were presented (Helmi et al. 2003), a substantial amount of observational work has been published. Crane et al. (2003) obtained spectra for a set of candidate giant stars from the 2MASS catalogue, which are apparently physically associated with the ring. They found that the giants exhibited a trend in velocity with Galactic longitude, similar to that shown in Figure 1. Martin et al. (2003) were able to identify a significant asymmetry in the 2MASS giant distribution at  $l = 240^\circ$  and  $b = -8^\circ$ , which they interpret as the core of a dwarf galaxy, the progenitor of the ring-like structure of Y03 and I03.

These studies, then, seem to confirm the tidal arc scenario and lend support to the idea that we are currently witnessing the accretion of a dwarf galaxy.

The orbital properties of the accreted satellite have not yet been established. Such a low-inclination merger has probably had some effect on the Galactic disk, but it is not clear whether there is any evidence for this nor what the precise signatures should be. It is intriguing that the stars in the ring seem to share similar kinematics to those of the Galactic thin and thick disks, although projection effects may be important (see Figure 2 of Crane et al.). The velocity dispersion of the giants is smaller than found in the solar neighborhood for these components, but this would be not be inconsistent with the trend of decreasing dispersion as a function of radius observed in other disk galaxies (Kregel 2003).

The shells discussed here are probably not responsible for the ring discovered by the SDSS. It is likely, however, that similar structures, the result of more ancient merging events, would be present in our Galaxy and may well be the most evident features in surveys of nearby stars.

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### Discussion

*Lynden-Bell:* What fraction of the angular momentum is in this ring?

*Helmi:* It is hard to estimate that at the moment since we only have a handle on the radial variation along a small portion of the ring. This makes it difficult to measure the contribution of the tangential velocity and hence angular momentum. In our models the orbits are fairly radial, which implies that the

contribution to the total angular momentum of the galaxy would be relatively small.

*Newberg:* The Gilmore paper actually proposed that the extra stars were part of a merger that was responsible for puffing up the thick disk, rather than that the thick disk was created from mergers. Is it possible that the stars in the “ring” are part of the same merger?

*Helmi:* The thick disk, if the result of heating up by a minor merger, should also contain debris from that event. It is therefore possible that the stars in the ring also originated in that minor merger, but more detailed modeling is needed to explore this scenario.

*Martínez-Delgado:* From my surveys of the Sgr Stream in selected low reddening, low galactic latitude fields close to the Galactic Center, I find that this Stream is not present in a range of heliocentric distances of 20–30 kpc. Could this constrain your different models in some way?

*Helmi:* Yes, in principle one expects rather different spatial distributions in each scenario. In the tidal arc case, one would probably expect the material to come closer to us, but also that the material should have lower density and may therefore be difficult to detect.

